Crack Detection in Armor Plates Using Ultrasonic Techniques

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Abstract— **A method of using piezoelectric lead zirconate titanate (PZT) transducers to characterize the vibrational modes of Vehicle Body Armor Support System (VBASS) plates and its preliminary results are presented. The amplitude of the vibrational modes of undamaged plates are compared to the vibrational mode amplitudes of damaged plates and shown to be clearly different. Plates for testing are damaged either by a blunt impact to the ceramic plate surface or cracked using a machine shop press. Data from these tests will be used to design prototype hand-held devices for the nondestructive testing (NDT) of plate structural integrity in the field. VBASS plates are used as proof-of-principle samples in the absence of vest body armor samples.**

***Index Terms*— armor plates, ceramic, NDT, PZT transducers**

I. INTRODUCTION

VARIOUS types of body armor comprised of Silicon Carbide (SiC) ceramic plates are in wide-spread use by the US military because of its relatively light weight and the ballistic protection offered to soldiers. The protection is diminished if the plate's integrity is compromised. Any number of things can induce cracks in the SiC plates, therefore it is important to inspect them after manufacturing and prior to shipping. There have been efforts to inspect VBASS plates using a fixed laboratory based device [1], however, this is inefficient and not always possible. A hand-held device used in ascertaining the health of body armor plates in the field is being developed.

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To achieve this, PZT transducers were used to excite flexural mode waves in the VBASS ceramic armor plates and to measure the resulting transmission signal of these plates. The authors found that there is a clear difference between damaged and undamaged plates. Fig. 1 below shows the structural composition of a VBASS plate.

Fig. 1: Structure of VBASS plate

shown in Fig. 1 above, VBASS plates have three basic components to them; 1. An outer canvas layer, 2. A ceramic impact plate, and 3. a composite inner layer that stops spalling from the round. The VBASS plates are being used as a material to test the efficacy of various prototype hand-held units to inspect the plates for cracks. It is envisioned that the hand-held devices will be used to perform plate inspection in the field, away from a laboratory based inspection system. Initially, a baseline measurement of the undamaged plate vibration data is obtained in the laboratory environment and will be stored in the hand-held device for later reference.

II. METHODOLOGY

To maximize the contact between the piezoelectric PZT transducers and the plate, a small area of the canvas was removed along with a thin layer of the adhesive used to keep the canvas on the plate. The transducers were then placed on the exposed parts of the plate and bonded to the two ends of the ceramic plate using epoxy.
An alternating voltage is then applied to the piezoelectric transducer on the left in Fig. 2 to cause it

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 MAR 2007	**N/A**	**-**

4. TITLE AND SUBTITLE
Crack Detection in Armor Plates Using Ultrasonic Techniques (PREPRINT)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Meitzler,Thomas,J; Smith,Gregory; Charbeneau,Michelle; Sohn,Euijung; Bienkowski,Mary; Wong,Ivan; Meitzler,Allen,H

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
18532 RC

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
TACOM/TARDEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
18532 RC

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Submitted for publication in "The American Society for Nondistructive Testing" - Materials Evaluation

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**6**	

to vibrate. This movement excites a mechanical wave in the plate which forces the transducer on the right to vibrate and generate electrical signals. These signals are measured using an oscilloscope. The basic idea of this technique is to use the signal generator to sweep through a frequency range of a few hundred kHz to characterize the response of undamaged plates and then to use that as a baseline to determine the condition of other plates. Undamaged plates have unique elements in their outputs that are affected by structural changes. When these unique elements are altered it indicates a change in structure or damage.

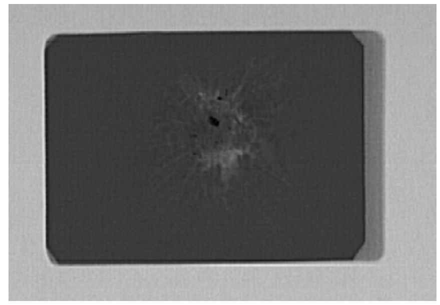

Fig. 4: X-ray image of damaged plate

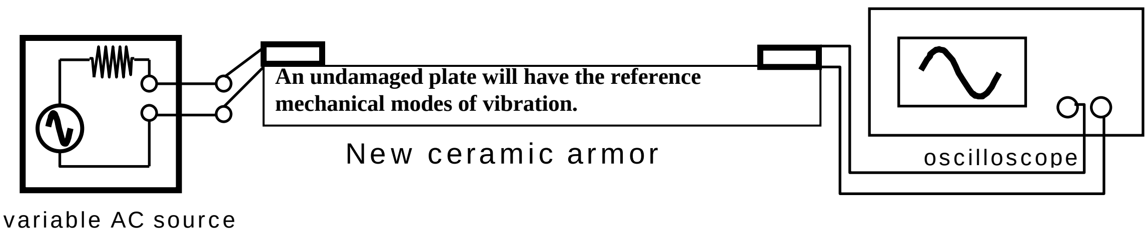

Fig. 2: Schematic of the test circuit with a ceramic plate

III. DATA

Plates were damaged in three ways and then analyzed with the aforementioned ultrasonic technique. The three modes of damage studied were; 1. projectile induced, 2. blunt impact damage, 3. crack induced in the plate by a five-ton press. All the plates were imaged with an in-house x-ray machine used for NDT. The plate in Fig. 3 below is the undamaged plate and the plate in Fig. 4 is the plate with cracks and a bullet hole. Discussion with in-house armor team members have indicated that the case of a plate with a clean bullet hole is very rare, usually there are cracks associated with a penetration of the plate.

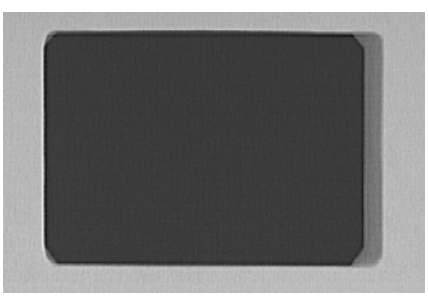

Fig. 3: X-ray image of undamaged plate

In Fig. 5, the topmost waveform is the input voltage at a resonant frequency of the plates, which is close to 63 kHz, that drives the PZT transducers, the middle waveform is the resonant vibration of the undamaged plate at around 63 kHz and the lower waveform is the resonant vibration of the plate with the cracks and bullet hole in it shown in Fig. 4.

Fig. 5 clearly shows that there is a difference in the shape of the voltage amplitude wave, indicating different plate vibrational resonances. Fig. 6 demonstrates a VBASS plate that has only an internal hairline crack. The key seen in Fig. 6 was used as an indicator of where the crack is located within the plate because the crack is hard to see with the naked eye.

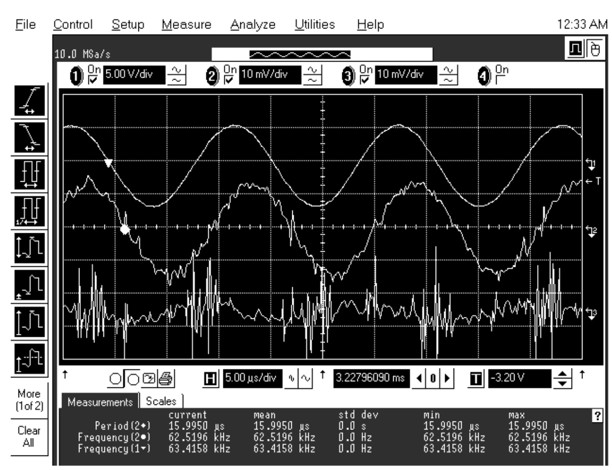

Fig. 5: Oscillogram of input and output voltages

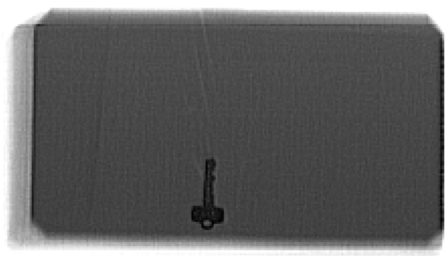

Fig. 6: X-ray image of a VBASS plate with a hairline crack

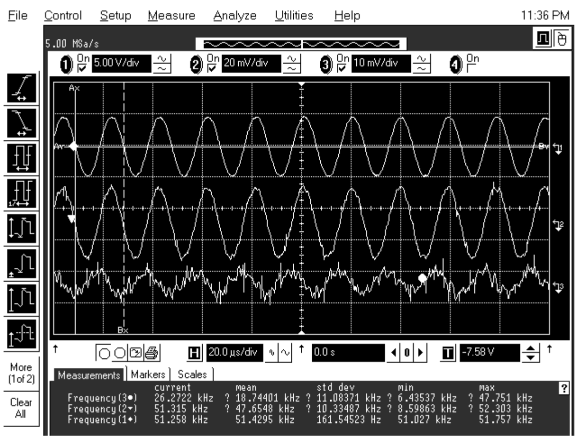

Fig. 7: Oscillogram of input and output signals using the hairline cracked VBASS plate

In Fig. 7 above, the topmost waveform is the input signal at a different resonant frequency of the plates, which is close to 51 kHz, that drives the PZT transducer, the middle waveform is the resonant vibration of the undamaged plate at around 51 kHz and the lower waveform is one of the resonant vibrations of the plate with the hairline crack in it shown in Fig. 6. Again there is a difference in the responses of the cracked and un-cracked plates.

The charts in Fig.'s 8 and 9 correspond to voltages measured using ring PZT transducers attached to the cracked and un-cracked plates. Fig.'s 10 and 11 correspond to measurements made using rectangular transducers. The charts in Fig's 10 and 11 correspond to the same plate that was measured first as an undamaged plate and then later measured again after it was damaged by striking it a couple of times with a hammer. Again, there is a vibrational frequency difference between the damaged and undamaged plate. The ring transducers were used in the beginning of our tests because of their availability, and later on we switched to rectangular transducers once an appropriate supplier was found.

Charts in Fig's 8 and 9 are included because at the time of the writing of this paper, the only cracked plate available was with the ring transducers. Using the rectangular transducers, we found that the rectangular PZT transducer output voltages to be higher in amplitude then the ring transducers and therefore it's possible to see more vibrational harmonics.

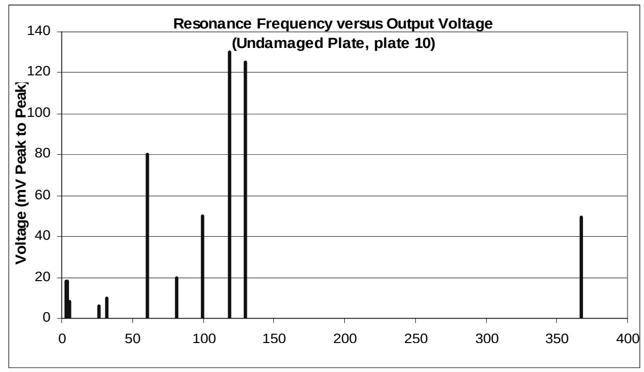

Fig. 8: PZT transducer voltage vs. frequency for undamaged plate

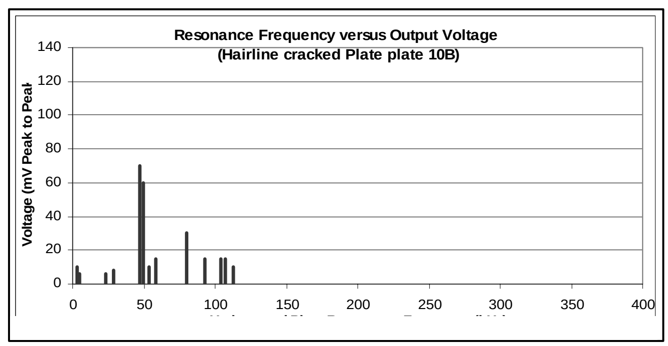

Fig. 9: PZT transducer voltage vs. frequency for the hairline cracked plate

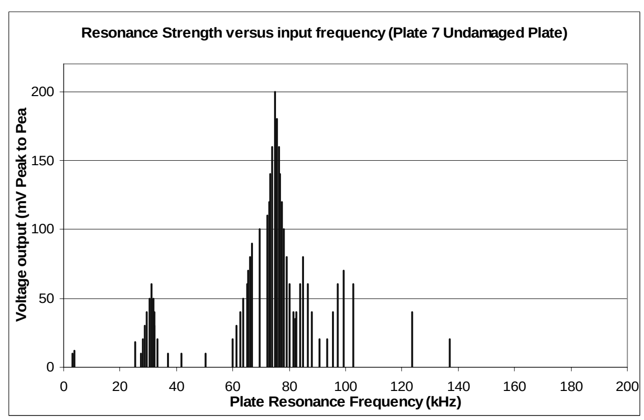

Fig. 10: PZT transducer voltage vs. frequency for undamaged plate

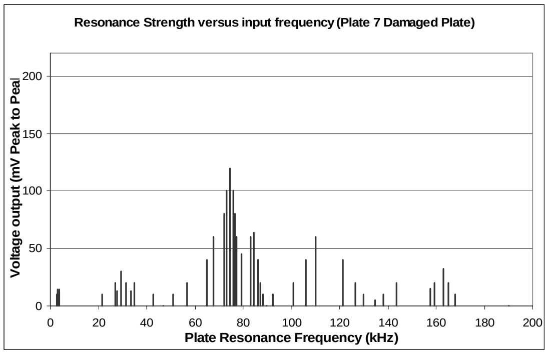

Fig. 11: PZT transducer voltage vs. frequency for damaged plate

Fig.'s 12, 13, and 14 are the x-ray image of a plate with a large crack though the center of the plate, and the graphs of the undamaged and cracked PZT voltages versus frequency. The rectangular PZT transducers are shown on the edges of the plate.

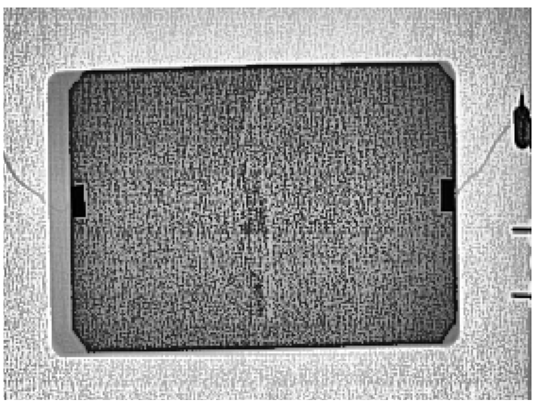

Fig. 12: X-ray image of VBASS plate3 with a crack through the center of the plate

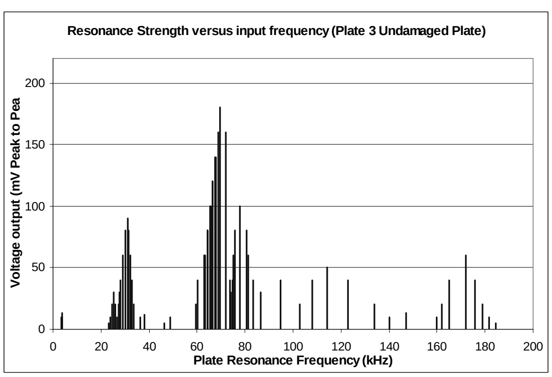

Fig. 13: PZT transducer voltage versus frequency for damaged plate

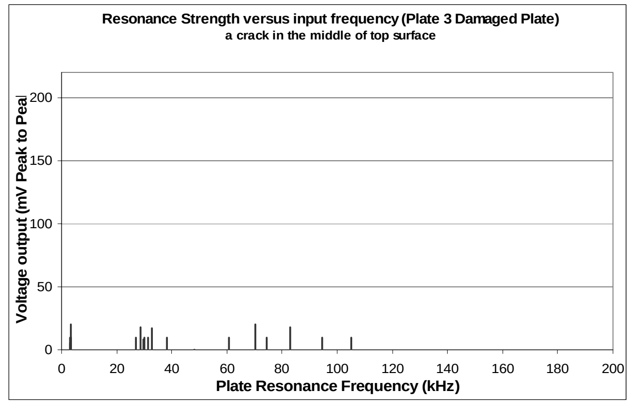

Fig. 14: PZT transducer voltage for the cracked plate using rectangular transducers

IV. ANALYSIS

The natural vibration mode frequencies of the plate under study were computed and compared to the measurements made with the PZT transducers. Calling "w" the plate deformation, the equation of motion for a plate under various boundary conditions is derived by Leissa [2, 7] and is,

$$D\nabla^2 w + \rho \frac{d^2 w}{dt^2} = 0, \qquad (1)$$

where D is the plate stiffness defined by,

$$D = \frac{Eh^3}{12(1-\nu^2)}. \qquad (2)$$

and E is Young's modulus, h is the plate thickness, ν is Poisson's ratio, ρ is the mass density per unit area of the plate, ∇^2 is the three-dimensional Laplacian operator, and t is the time. A table of the constants and physical dimensions of the plate that are used in the computation of the resonant frequencies are provided below in Table I. The solutions to the equation of motion are the frequencies of vibration of the plate and are graphed in Fig. 15. As can be seen in the chart of Fig. 15, there are groups of resonant frequencies approximately every twenty kHz.

$$\omega_{mn} = \sqrt{\frac{D}{\rho}\left\{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2\right\}} \qquad (3)$$

In Fig. 13 the group of frequencies around 70 kHz corresponds with the fundamental resonant frequency of the PZT transducer at 69 KHz which was determined from admittance measurements of un-bonded transducers.

TABLE I: PHYSICAL CONSTANT AND PLATE VALUES [3]

Young's Modulus	401.38 GPa
Poisson's Ratio	0.1875
Plate length, a	33 cm
Plate width, b	17.8 cm
Plate depth, d	2.4 cm
Volume	660 cm^3
Density	4303 kg/m^3

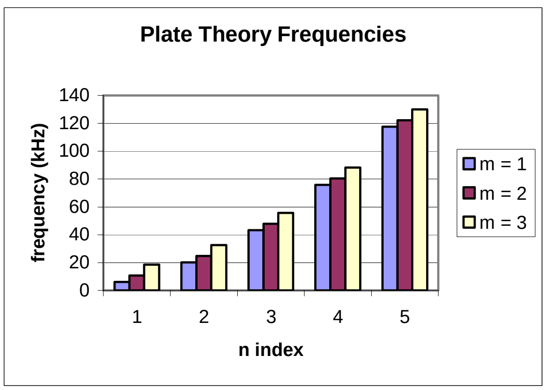

Fig. 15: Chart of computed frequencies of the VBASS plate

V. Future Efforts

One of the goals of this research is to develop a device that can test for the existence of cracks in armor plates in the field, away from laboratories or test equipment. The prototype device is based on the "impact method" and a schematic of the prototype is shown in Fig. 16. (An excellent review of the ultrasonic "impact method" is provided in the Evans [4] patent as well as other texts on NDT [5,6].) This device would be held over the armor sample and pushed against the plate to release the plunger. This action will send a shockwave through the plate which can be picked up by a ring transducer inside the device for measurement and comparison. Presently the device is attached to an oscilloscope for signal analysis. In the future, it is planned to have an integrated MEMS device collect and perform the required data and signal analysis.

Currently a hand-held test unit is being developed that will implement the continuous signal transmission testing that is outlined in the beginning of this paper.

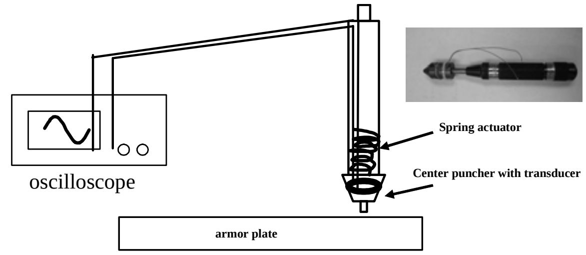

Fig. 16: Hand-held "impact method" prototype

VI. Conclusions

PZT transducers can be used to characterize the response of ceramic armor plates at a range of frequencies. The presence of a hairline crack in the VBASS plates can easily be identified by comparing its voltage waveforms against that of an undamaged plate using the bonded transducer approach. The authors have recently demonstrated a working prototype of a portable, handheld test unit. Research and development is currently underway to develop more robust hand-held devices for armor crack detection in the field based on the data from the experiments mentioned above.

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Thomas J. Meitzler (M ''83) was born May 5, 1955 in Allentown, PA. He obtained a B.S. and M.S. in Physics from Eastern Michigan University, attended the Univ. of Michigan, and received a Ph.D. in Electrical Engineering from Wayne State University in Detroit, MI.

Dr. Thomas Meitzler has taught Physics, Astronomy and Engineering courses at The University of Michigan-Dearborn and Henry Ford Community College. From 1988 to present he has been a research engineer at the U.S. Army Tank-Automotive Research and Development Engineering Center in Warren in the department of Survivability Technology. He has published papers on infrared and visual detection computational methods, detection probability and infrared electro-optic system simulation.

Dr. Thomas Meitzler is a co-winner of the 1995 U.S. Army Research and Development Achievement award and has several patents. His research interests include sensor and image fusion, ultrasonic non-destructive testing and imaging, functional magnetic resonance imaging, 3D- imaging technologies and high fidelity photo-simulation. He is currently involved in cooperative research efforts with NASA's Kennedy Space Center and Columbia University Medical School.

Gregory Smith graduated from the University of Michigan with a Bachelors of Science Electrical Engineering, 1968

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Primary Experience: Remote Sensing Research and Advanced Engineering. This includes concept, design, prototype build, test and evaluation for applications ranging from anti-submarine warfare to automotive active safety.

Allen H. Meitzler (M'56–SM'75–F'81–LF'94) was born December 16, 1928 in Allentown, PA. He obtained a B.S. degree in Physics from Muhlenberg College in Allentown and M.S. and Ph.D. degrees in Physics from Lehigh University in Bethlehem, PA.

He joined Bell Telephone Laboratories (now called Lucent Technologies) in October 1955 and was there as a member of the Technical Staff of Telephone Laboratories until September 1972, when he joined the Research Laboratory of the Ford Motor Co. in Dearborn, MI. He retired from Ford on January 1, 1996. Over the years, Dr. Allen Meitzler has had a strong interest in the development of IEEE standards. He chaired the Piezoelectric Standards Subcommittee over the 14-yr period taken to develop IEEE Standard 176-1978, "IEEE Standard on Piezoelectricity". He was active in the preparation of the IEEE Standard 180-1986 and chaired the Ferroelectric Standards Subcommittee when the work on that standard was brought to completion. Dr. Allen Meitzler has served the UFFC-S in a variety of positions since joining the IRE (predecessor of the IEEE) in 1955. He was the Vice- Chair (1962) and Chair (1963) of the Professional Group on Ultrasonics Engineering (the PGUE was the predecessor of the UFFC-S) and served as Secretary-Treasurer from 1965 to 1970. He is a Life Fellow of the IEEE and a Fellow of the Acoustical Society of America. Since retiring from Ford, Dr. Meitzler has continued to be professionally active, teaching part-time undergraduate electrical engineering courses at the University of Michigan - Dearborn. He has a small consulting business and is presently serving as an elected member of the UFFC-S Administrative Committee. For the past 3 yr, he has served as an Associate Editor of the *IEEE Transactions UFFC*.

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She has experience with business management, computer repair, computer hardware testing and evaluation, and computer programming. She is a computer engineer currently working on programming data acquisition systems with LabVIEW at the U.S. Army Tank Automotive RDEC in Warren, MI in the department of Survivability Technology.

Ivan Wong received his bachelor's degree in computer science engineering in 2007 from the University of Michigan in Ann Arbor, Michigan.

He is currently in his third year working at the US Army Tank Automotive Command LCMC in Warren, Michigan. He came onto the Visual Perception Lab team (now known as MGV Visual Testing and Analysis) in the summer of 2005 as a summer hire where he worked on evaluating cameras in high glare situations. In 2006, he returned as a co-op student to develop software for image assessment through the use of metrics.

Mrs. Euijung Sohn was born at Suwon, Korea in 1966. She immigrated to the U.S. in 1985 then she finished her high school degree in Park Ridge, IL. She studied at the University of Illinois and got her B.S. degree in Electrical Engineering in 1991. After her graduation, Mrs. Sohn was hired in Simulation department in US Army Tank Automotive Command in 1991.

Mrs. Sohn has worked as a research engineer from 1992 to present in the Survivability Technology Center. She has been involved in the validation, and verification of thermal and visual detection models and atmospheric propagation studies.

Mrs. Sohn is now involved in planning, testing, and analyzing visual perception test of military ground vehicles and commercial vehicles. She is also involved in NASA ice detection research program and target detection research using fMRI of brain activities. Mrs. Sohn has authored and co-authored technical papers in the area of infrared and visual system simulations and target detection. Mrs. Sohn was a recipient of the 1995 Army Research & Development Award for the Computational Vision Model Development for Dual-Use Applications.

Mary E. Bienkowski is a Mechanical Engineer for the MGV Visual Testing and Analysis Team (MGV-VT & A), for Survivability team of the Research Business Group (RBG), at the TARDEC-RDECOM in Warren, Michigan as of 2003. Initially, she was hired to the TARDEC's Robotics Mobility Team as an engineering co-op student and aided with the statistical analysis of user training times for the Omni-Directional Inspection System (ODIS) robots for soldier support (2003-2004). Her most recent research involves working with NASA's Kennedy Space Center (KSC) developing and analyzing non-destructive electro-optics test methods for the NASA ice debris and inspection system used for external shuttle tank, in support of the Army and NASA SAA (Space Act Agreement). She is also actively participating in the implementation of future ultrasound non-destructive assessment for body armor plates applications with TARDEC's Rapid REF Team to provide a quick inspection test method for armor deployment by determination of the structural integrity of damaged body armor plates. Additional research includes collaborative work with Dr. Joy Hirsch of the Columbia University's functional Magnetic Resonance Imaging (fMRI) Research Center for developing a rapid method of detection for stealth assessment and camouflage testing using fMRI applications. Further initiatives that she helped ruggedize the housing unit of the Panoramic Image Fusion (PIF) system in efforts of vehicle 360-degree situational awareness (SA).